Effect of tidal regime on estuarine residence time spatial variation

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Abstract: - The hydrology and the ecology of shallow estuaries are strongly influenced by the freshwater inflow and the adjacent open sea, due to tide and wind generated water exchange, creating salinity gradients, thermal stratification and assuring large transport of silt, organic material and inorganic nutrients into the estuarine waters. Nutrient enrichment is a key-factor for habitat degradation, leading to sensible structural changes in estuarine ecosystems with the consequent occurrence of episodic algal blooms.

In the last two decades, the south arm of the Portuguese river Mondego estuary was stressed by an eutrophication process due to massive nutrient loading from urbanised areas and from intensively agricultural land runoff.

The aim of this work is to calculate estuarine water residence time values, which are broadly recognised as important descriptors of estuarine circulation patterns and constitute key-parameters to assess estuarine eutrophication vulnerability. In fact, estuaries with nutrients residence time values, shorter than the algal cells doubling time, will inhibit algae blooms occurrence. The increase of estuarine flushing capacity can be seen as a management measure to mitigate or to invert eutrophication processes.

In this work, the *MONDEST* model, a 2-DH water quality model, was developed and applied to calculate water residence time, at different simulated management scenarios. The results shows the effect of simulated tides on the spatial distribution of estuarine residence time values, which are related with the eutrophication gradients, observed in the Mondego estuary south arm during the last decades. This integrated model constitutes a powerful tool to support authorities' decisions concerning the best water management practices and restoration measures for the environmental sustainable management of this complex ecosystem.

Key-Words: - estuarine water management; numerical modelling; eutrophication; residence time; Mondego estuary.

1 Introduction

Estuaries and coastal lagoons are commonly subjected to intensive anthropogenic stress due to massive pollutant loading from urbanised riverain areas. According to a strategic EU document [1], research and technological development play an important role in the implementation of the Water Framework Directive (WFD), in order to improve the knowledge about the pressures and ecological status of the aquatic ecosystems.

Excessive organic carbon input associated with nutrient enrichment, leading to eutrophication of estuarine and coastal waters is widely recognized as a major worldwide threat [2; 3]. As a response to this, there has been an enormous increase in restoration plans for reversing habitat degradation, based on knowledge of the major processes which driven the observed ecological changes.

Much progress has been made in understanding eutrophication processes and in constructing modelling frameworks useful for projecting the effectiveness of nutrient reduction strategies [4].

The influence of hydrodynamics must not be neglected on estuarine eutrophication vulnerability assessment, as flushing time affects the transport and the permanence of water and its constituents inside an estuary [5]. Estuarine water residence time (WRT) has a strong spatial and temporal variability, which is accentuated by exchanges between the estuary and the coastal ocean due to chaotic stirring at the mouth. So, the concept of a single WRT value per estuary, while convenient from both ecological and engineering viewpoints, is therefore shown to be an oversimplification [6].

Residence time (RT) values, related with the water constituents (conservatives or not) permanence inside an aquatic system, are broadly recognised as important descriptors of estuarine circulation patterns and, so, a convenient parameter representing the time scale of physical transport processes, often used for comparison with time scales of biogeochemical processes [7]. In fact, estuaries with nutrients residence time values, shorter than the algal cells doubling time, will inhibit algae blooms occurrence.

The increase of primary production rate in river systems when the flows decrease can also be attributed to higher residence time values [8; 9]. Dettmann [10] used RT and a first-order biogeochemical rate coefficient on a simple two-parameter model to illustrate the relative contribution of the physical transport and biogeochemical processes in estuaries. RT spatial distribution can play a special role in estuarine eutrophication vulnerability assessment, by identifying the most sensitive areas [11].

The Mondego river basin is located in the central region of Portugal, confronting with Vouga, Lis and Tagus, and Douro river basins. The drainage area is 6670 km^2 and the annual mean rainfall is between 1000 and 1200 mm.

The Mondego estuary (40º08'N 8º50'W) is divided into two arms (north and south) with very different hydrological characteristics, separated by the Murraceira Island (Fig. 1). In the south arm of this estuary, eutrophication has triggered serious biological changes, which led to a progressive replacement of *seagrasses* (*Zostera noltii*) by opportunistic macroalgae.

Fig. 1 Location and aerial view of Mondego estuary

Episodic macroalgae blooms (Fig. 2) have been observed in the southern arm of the Mondego estuary, due to the simultaneous occurrence of high water residence time [12] and high availability of nitrogen and phosphorus, discharged from oriziculture and aquaculture activities.

Fig. 2 Macroalgal bloom in Mondego estuary

This work presents a 2D-H water quality model for Mondego estuary (*MONDEST model*), which was developed in order to simulate its hydrodynamic behaviour, salinity and residence times spatial distributions, at different simulated management scenarios. This model was calibrated and validated using data obtained from the sampling programs carried out over the past two decades [13].

Some hydrodynamic simulation results are presented to illustrate the strong asymmetry of flood and ebb periods at the inner sections of this estuary, as well the tidal prism and flows estimation. The assessment of tidal regime influence on estuarine RT values and spatial variation is the main objective of this work, in order to analyse its impact on the flushing capacity of this complex aquatic ecosystem.

The conclusions of this and other studies allowed to support successful mitigation and restoration measures, based on nutrient discharges reduction, river Pranto local discharge change and hydrodynamic circulation improvement. After the implementation of those restoration measures, no macroalgae blooms were yet observed.

2 Methods

2.1 Sampling program

The north arm is deeper and receives the majority of freshwater input (from Mondego River), while the south arm of this estuary is shallower (2 to 4 m deep, during high tide) and is almost silted up in the upstream area (Fig. 3).

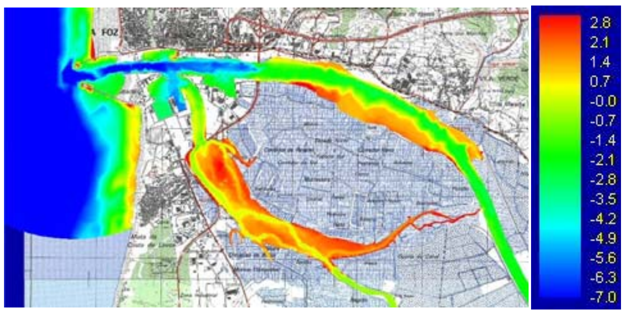

Fig. 3 The Mondego estuary bathymetry (high tide)

Consequently, the south arm estuary water circulation is driven by tide, wind and the usually small freshwater input of Pranto River, a tributary artificially controlled by the *Alvo* sluices near its mouth.

For the eutrophication process assessment, it became crucial to obtain information about the mechanisms that regulate the abundance of opportunistic macroalgae and its spatial and temporal distributions.

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A sampling program was carried out during last two decades at three benthic stations and at three other sites: river Pranto sluice, Armazéns channel mouth and Gala Bridge for water column monitoring. The choice of benthic stations was related with the observation of an eutrophication gradient in the south arm of the estuary, involving the replacement of eelgrass, *Zostera noltii*, by opportunistic green algae, such as *Enteromorpha spp.* and *Ulva spp.* [14].
Water level, velocity, salinity, dissolved oxygen and water samples were collected every half-hour for physical and chemical characterization of this system. Depending on the tidal amplitude, depth, cohesiveness of plant material, current velocity, wind and wave-induced vertical turbulence, plants growing in shallow areas are suspended in the water column and transported out and eventually settled in deeper areas.
In this system, available data analysis allows to conclude that the occurrence of green macroalgae blooms is strongly dependent on the flushing conditions, salinity gradients and nutrient loading [15].

2.2 Mathematical modelling

Numerical modelling is a multifaceted tool to get a better understanding of physical, chemical and biological processes in the water bodies, based on a "simplified version of the real" described by a set of equations, which are usually solved by numerical methods.
The formulation of a model requires the better (possible) definition of the geometry and bathymetry of the water body and the interactions with the surrounding processes occurring in its boundaries (boundary conditions).
The models to be used for the implementation of the WFD should ideally have the highest possible degree of integration to comply with the integrated river basin approach, coupling hydrological, hydrodynamic, water quality and ecological modules as a function of the specific environmental issues to analyse [15].
The Mondego Estuary (*MONDEST*) model was conceptualized integrating hydrodynamics, water quality and residence time (*TempResid*) modules (Figure 3), based on generic models [16], [17] adapted to this specific estuarine ecosystem (Fig. 4). The hydrodynamic model provides flow velocities and water levels for the water quality module, which acts as input on *TempResid* module, feeding constituents (tracer, nutrients) concentration values over the aquatic system.

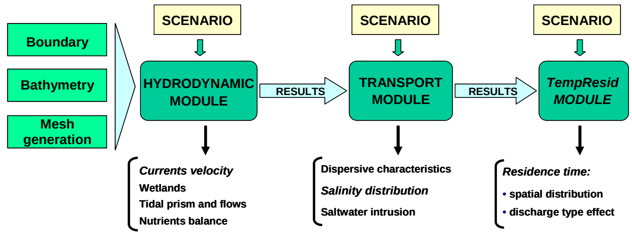

Fig. 4 The *MONDEST* model conceptualization

The *TempResid* module was developed for RT values calculation for each constituent over all the system, allowing mapping RT spatial distribution at different simulated management scenarios [5].
For analyse and comparison of the simulation results several control points were defined in both Mondego estuary arms: north (N1-N6) and south (S1-S5), as depicted in Figure 5.

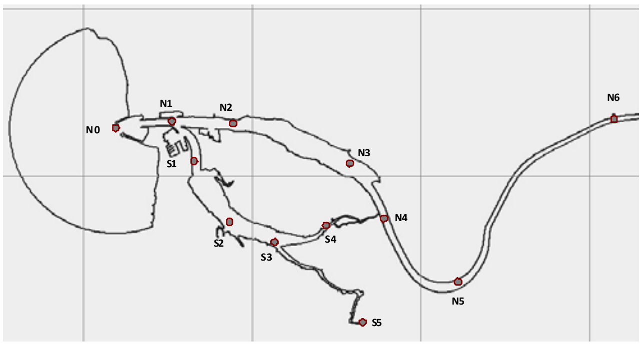

Fig. 5 The Mondego estuary control points

A wide range of management scenarios were judiciously selected considering a representative set of tidal amplitudes (0.60, 1.15 and 1.60 m), river flow inputs (Mondego and Pranto), load characteristics and constituent decay rates (Table 1).

Table 1. Simulated management scenarios for estuarine residence time calculation

SCENARIO	RIVER FLOW ($m^3.s^{-1}$)		TIDE	LOAD	DECAY RATE (day^{-1})
	Mondego	Pranto			
RT 1	15	0	medium	point	0
RT 2			spring		
RT 3			neap		
RT 4			medium		1
RT 5					10
RT 6		15			0
RT 7	1	0			
RT 8	75				
RT 9	340				
RT 10	15			diffuse	
RT 11					1
RT12	75				0
RT 13					1
RT 14					0,5

3 Results and discussion

3.1 Model calibration and validation

This work presents the *MONDEST* model results obtained for different tides – medium, spring and neap (scenarios RT1, RT2 and RT3, respectively) – in order to assess the effect of tidal regime on estuarine residence time spatial variation.

The velocities and water levels field data, obtained from sampling program, were used for model calibration and validation (Fig. 6), as well as to define accurate boundary conditions to introduce on hydrodynamic and transport modules.

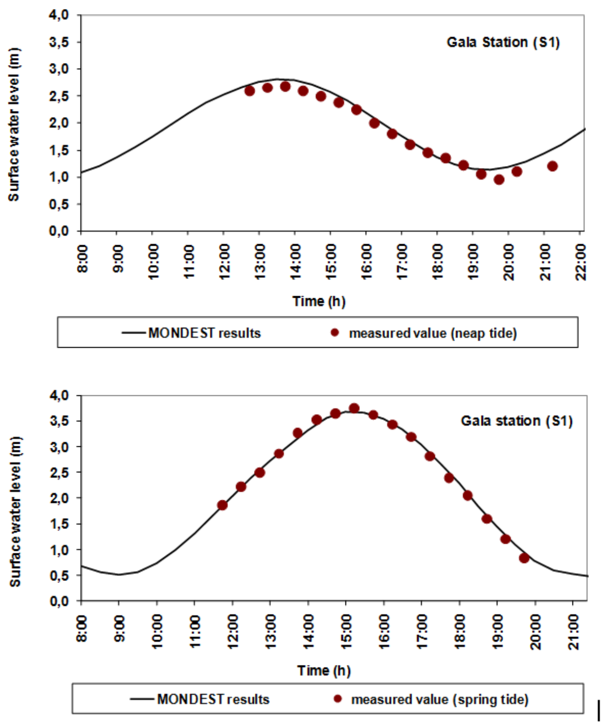

Fig. 6 Hydrodynamic module calibration (spring tide) and validation (neap tide) at Gala station (S1)

The *MONDEST* transport module calibration (Fig. 7) and validation was performed with the salinity field data, in order to estimate the estuarine dispersion coefficients, which allowed us to achieve the better correlation between model results and sampling data.

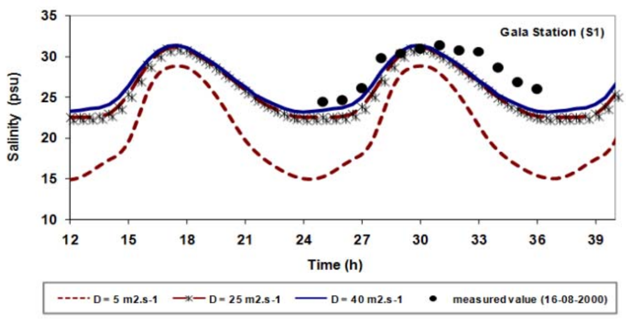

Fig. 7 Transport module calibration (Gala station)

Hydrodynamic results allowed the evaluation of the magnitude of currents velocity in both arms during ebbing (Fig. 8) and flooding situations, and to assess the influence of tidal regime.

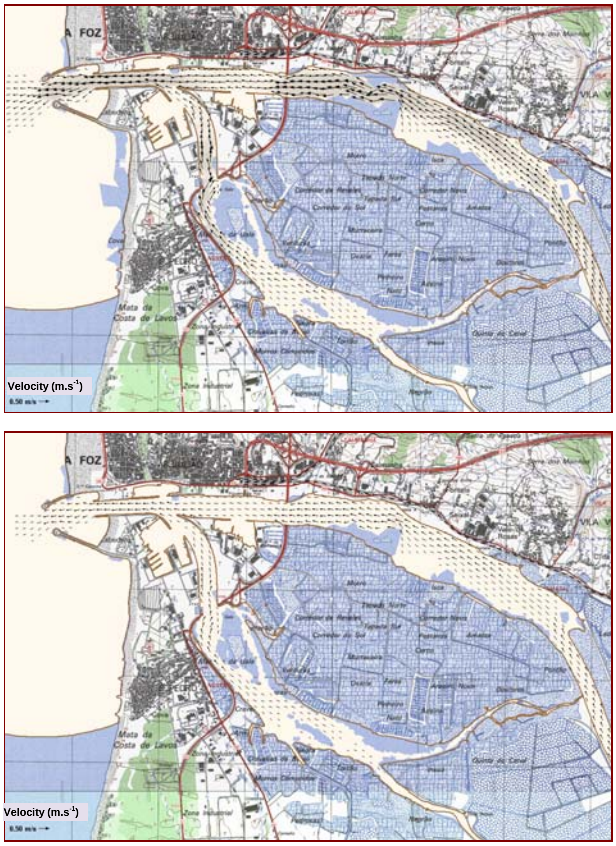

Fig. 8 Effect of tidal regime on currents velocity magnitude (flooding and dry-weather conditions)

For dry weather conditions, the higher velocity values obtained in the southern arm occur near Gala Bridge, reaching 0.35 (neap tide, RT3) to 0.70 $m.s^{-1}$ (spring tide, RT2), while in the northern arm these values are lower, reaching 0.33 (neap tide) to 0.60 $m.s^{-1}$ (spring tide), at 1km upstream the Figueira da Foz bridge.

Figure 9 presents a synthesis of tidal prim values at two control points: one, near the Modego estuary mouth (N0) and, the other, in the south arm, downstream Gala bridge (S1).

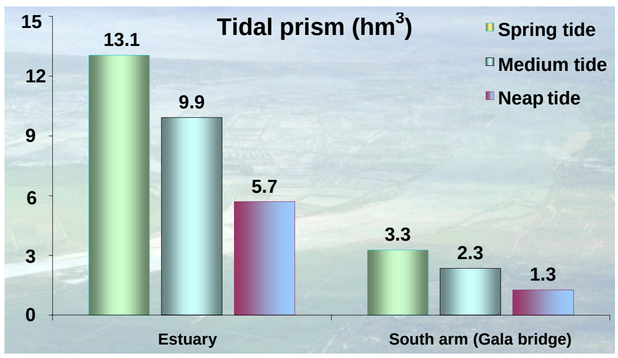

Fig. 9 Transport module calibration (Gala station)

These values were calculated applying *MONDEST* hydrodynamic module to the simulation scenarios RT1, RT2 and RT3, considering three different tidal amplitudes, representing typical tides observed in this estuarine system, and the same dry weather condition: river Mondego flow of 15 $m^3 \times s^{-1}$ and no river Pranto input (sluices closed). As we can see in this graph, tidal amplitude has a great influence on tidal prim values estimated at both control points, corresponding to a water volume reduction of 56% e 61%, according to a spring or a neap tide are considered.
The simulation results allowed us to identify some tidal prim asymmetries in the estuary north arm, concerning with the ebbing or the flooding periods. For spring and medium typical tides, ebbing tidal prism is 9% higher than the flooding one. But, during typical neap tide, flooding tidal prim exceed the ebbing one in 2%. However, in the south arm this asymmetries are irrelevant, being the differences lower than 0.3%.
Figure 19 shows an example of *MONDEST* model transport module results for management scenario RT1, one of the most favourable to macroalgae blooms occurrence, due to low freshwater inputs and consequent reduction of estuarine waters renovation.

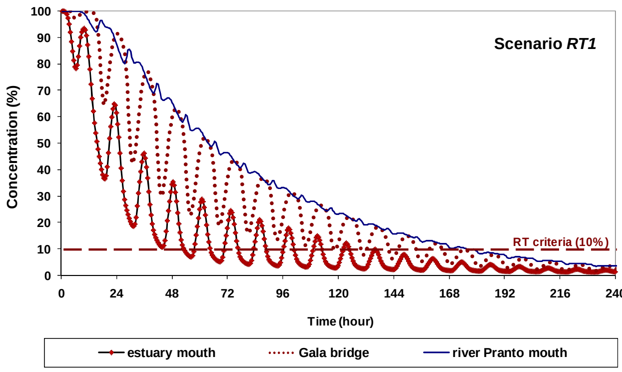

Fig. 10 Transport module calibration (Gala station)

This graph presents the concentration decrease of a conservative constituent, in three control points (N0, S1 and S3), due to estuarine flushing currents, considering the well known re-entrance phenomena at the estuary mouth.
During the warm season (late spring and summer), the Alvo sluices are almost closed. So, the salinity and the RT in the Mondego estuary south arm are strongly influenced by tidal regime. Concerning the periodicity of tidal regime recurrence, its effect could be very relevant only on estuarine biochemical processes with a time scale lower than 6 days.
Figure 11 illustrates the gradient of RT spatial distribution, which was mapped applying *TemResid* module computing availability for management scenarios RT2 and RT3.

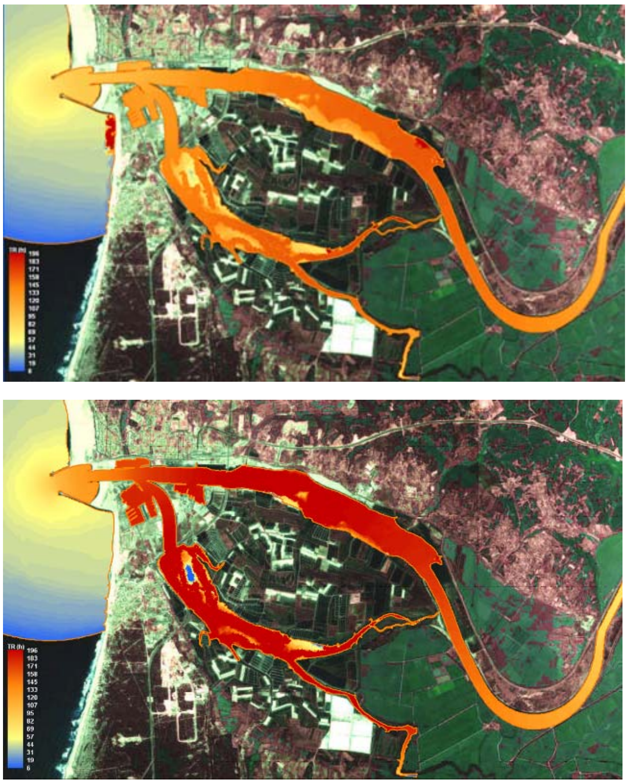

Fig. 11 Effect of tidal regime on RT values distribution (neap and spring typical tides)

Simulation results for these two tidal scenarios showed a RT values increase of 50% for a neap tide, when compared with a spring tide, both in south arm and in the north arm reach, between N1 and N2 control points. This increase is soothed in north arm inner areas, with de lowest increase (only 17%) at Modego estuary mouth.
The minimum RT values (3.2 days) occurred in the Mondego estuary mouth (N0) and in the mesothophic wetland zone of the south arm (station A). The maximum RT values (9.5 days) were obtained for the strongly eutrophicated zone (station C) of this estuary arm, near the Pranto River mouth.

4 Conclusions

Results obtained from hydrodynamic modelling have shown a strongly asymmetry of ebbing and flooding times at inner estuary south arm areas due to its complex geo-morphological patterns (wetlands and salt marshes). This information allows a more accurate tidal flow calculation which is the major driving force of the southern arm flushing capacity, when Alvo sluices rest closed.

In both arms of this estuary, the tidal prism volumes are strongly influenced by the bathymetry (extensive wetland areas), tidal regime and freshwater inputs.

Effectively, the River Pranto inflow absence (a typical summer situation) increases RT values drastically in the inner estuary southern arm and, consequently, the nutrients availability for algae uptake is higher, enhancing estuarine eutrophication vulnerability.

For medium typical tide, drought conditions and conservative constituents, *MONDEST* model results showed that estuarine RT values range between 6 days (at the both arms) and 4 days in the downstream reach of its two arms confluence (control point N1).

The *MONDEST* model developed and applied in this work allows us to evaluate and rank potential mitigation measures (like nutrient loads reduction or dredging works for hydrodynamic circulation improvement). So, the proposed methodology, integrating hydrodynamics and water quality, constitutes a powerful hydroinformatic tool for enhancing estuarine eutrophication vulnerability assessment, in order to contribute for better water quality management practices and to achieve a true sustainable development.

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